Design and Implementation of a Passive UHF RFID-Based Real Time Location System

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***Abstract*—A passive Ultra-High Frequency (UHF) Radio Frequency Identification (RFID) based Real Time Locating System (RTLS) is presented in the paper. For the validation, a reader has been developed and complemented with a tag modulator to form a complete UHF RFID-based real time locating system focused on backscattering communication. PN sequences have been used to measure the TOA and estimate the distance between reader and tag. A TX-to-RX leakage canceller has been applied in the reader RF front-end to increase the isolation and enhance the sensitivity. Measurement results indicate that the estimation accuracy in real time is about 1.6 meters and the mean estimation error of 1000 times' measurement in 1 second is less than 0.5 meter.**

***Index Terms*—Radio Frequency Identification (RFID), Real Time Locating System (RTLS), Time of Arrival (TOA), backscattering**

I. INTRODUCTION

Ultra-High Frequency (UHF) Radio Frequency Identification (RFID) is promising and increasingly interests many people due to the merits of long communication distance, high speed and large information capacity [1]. Depending on the existence of a built-in power source, tags in RFID system can be classified as passive, semi-active, and active. Active tags in RFID system contain built-in power sources for their proper operation. Passive tags, however, due to lack of built-in power sources, have to harvest power from the electromagnetic wave transmitted by the reader to supply their internal circuits. The communication mechanism of passive UHF RFID is based on backscattering, as shown in Fig.1.

Real Time Locating System (RTLS) is a wireless system with the ability to locate the position of an item or a person anywhere in a defined space at a point in time that is, or is close to, real time [2].Many different RFID-based localization systems have been developed and applied to lots of areas in recent years, like emergency rescuing, patient tracking, asset or livestock tracking, and many other areas [3-5].

According to the techniques of distance estimation, RTLS can be classified as: Time of Arrival (TOA), Angle of Arrival (AOA) or Direction of arrival (DOA), Received Signal Strength Indicator (RSSI) and so on. RTLS based on TOA technology detects transfer time of the signal to estimate the distance between the transceiver and the target. Some technologies of TOA-based RTLS have been reported. An indoor location system using RFID and ultrasonic sensors is realized in [6], but it needs additional sensors. Reference [7] introduces an active RFID location system based on time difference measurement using a linear FM chirp tag signal, but a linear FM chirp source should be included in the active tags. Multi-frequencies continuous-wave (CW) RFID Radar systems have been researched and discussed in [8], including a linearized model of the tag's reflection coefficient during backscatter modulation.

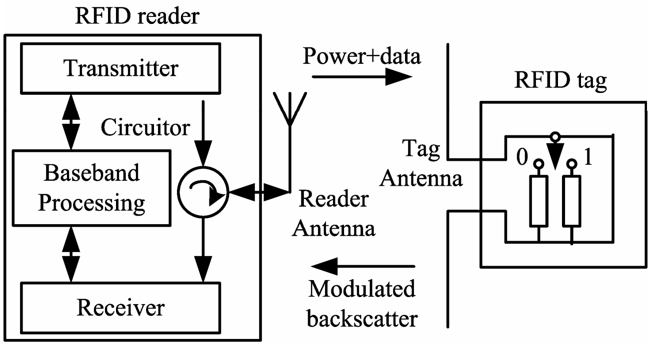

Fig. 1 Principle of UHF RFID

In this paper a TOA-based RTLS using passive UHF RFID is proposed. The rest of the paper is organized as follows: Section II describes the read architecture. Guidelines for the design of the system are put forward in this section. Section III presents measurement setups of the system. A backscatter modulator is developed in this section to represent a passive tag. Section IV discusses the measurement results. And finally, the conclusions are drawn in the last section.

II. SYSTEM ARCHITECTURE

In order to locate a tag in the effective operation area, RFID reader need to detect the distance and here Pseudo-random Number Ranging (PNR) method is introduced. Block diagram of the reader and flow chart of the system are shown in Fig.2 and Fig.3, respectively. RFID reader communicates with a tag entering the interrogation area and judges whether it need to locate or not. If so, a Pseudo-random Number (PN) sequence is transmitted by the transmitter (TX block) and at the same time, the tag modulates the received signal with a square signal and backscatters it to the reader. The received PN sequence is demodulated by the reader receiver (RX block) and correlated with the transmitted one in Digital Signal Processing (DSP) to get the TOA. As a result, the proposed TOA-based real time locating system contains a versatile reader and, however, an ordinary tag, to locate an object.

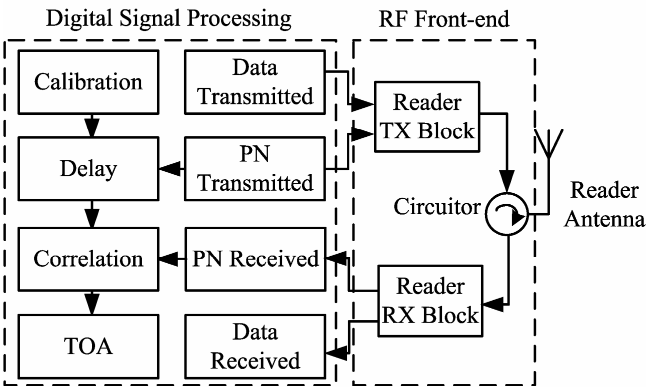

Fig. 2. Block diagram of the reader

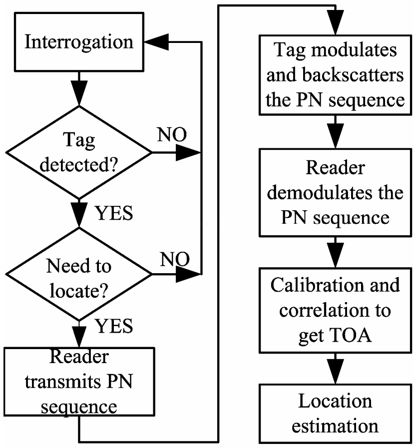

Fig. 3. Flow chart of the system

The system architecture of the reader is illustrated in Fig.4, including a direct conversion transmitter and a homodyne receiver. Only one local oscillator is used for both transmission and reception, which reduces the complexity of the reader and avoids the image frequency problems. However, several inherent constraints of the architecture should be considered.

One of the main challenges is the above mentioned TX-to-RX leakage. Generally a circulator or a directional coupler is utilized to separate the transmission path from reception path. However, both of them are difficult to increase the isolation to 25 dB. The large leakage will cause desensitization and block the receiver. A narrowband TX-to-RX leakage canceller covering UHF RFID frequency band is proposed to improve the isolation, as shown in Fig.4. The signal transmitted by the reader is routed through a directional coupler and breaks into two paths. One path is fed to a circulator. The other passes through a phase shifter and an attenuator, both adjustable, to achieve the anti-leakage signal. The two paths are mixed in a balanced power combiner to cancel the leakage. The proposed TX-to-RX leakage canceller is supposed to increase the isolation by about 20 dB, which will greatly suppress the leakage and improve the receiver's sensitivity [9].

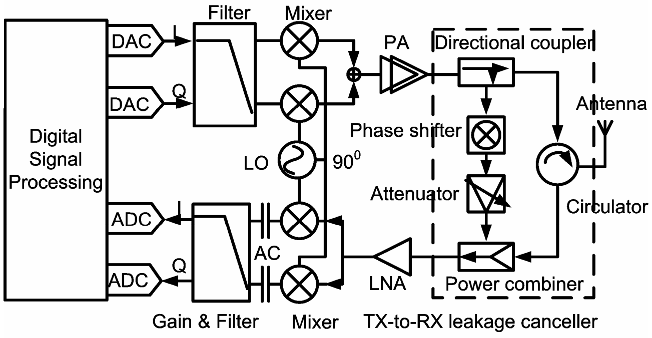

Fig. 4. System architecture of the reader

UHF RFID system also suffers from the detection gaps since the phase in the backscattered wave varies along time and distance [10]. The leakage, as well as other strong reflections, will mask the received signal and destroy the coherent detection. Thus an in-phase/quadrature (I/Q) demodulator is introduced to avoid detection gaps. When one path is at minimum sensitivity, the other is at the maximum and the communication is always guaranteed. In addition, a calibration should be carried out to cancel the phase shift caused by the target tag to get a real TOA.

Another constraint of the architecture is DC offset due to self-mixing or large reflections received at the antenna. An ac coupling stage is added in as the first element in the baseband chain to eliminate the offset. It avoids the signal from distortion due to saturation in baseband stages. However, it can't eliminate the leaking PN sequence in this system and a variable gain amplifier (VGA) with a narrow gain range (0~20dB) is required. 12 bits Analog-to-Digital Converters (ADCs) with a wide dynamic range are applied to avoid the baseband signal from being ruined by quantized noise. The anti-aliasing filter and the ADCs are designed to work up to 3 MHz baseband bandwidth.

III. MEASUREMENT SETUP

In order to validate the designed reader and the general system, a backscatter modulator has been designed and fabricated to represent the target tag, as shown in Fig.5. It contains a tag antenna, an RLC network, a switch, a frequency divider and a crystal oscillator. Although a power source is included in the modulator, the communication mechanism is still based on backscattering, just like a passive tag. The tag antenna was designed using Ansoft HFSS for antenna gain and impedance calculation, and then fabricated and measured by an Aglient network analyzer. The measured impedances are 39.6+j160.3 Ω @900MHz, 39.9+j166.8 Ω @915MHz, 40.8+j175.2 Ω @925MHz. The values for the inductance and capacitance in Fig.5 are 10 nH and 2.5 pF, respectively. The fabricated tag modulator switches the input impedances between two states according to the data signal. The switch's on-off frequency varies among 40 kHz, 80 kHz and 160 kHz.

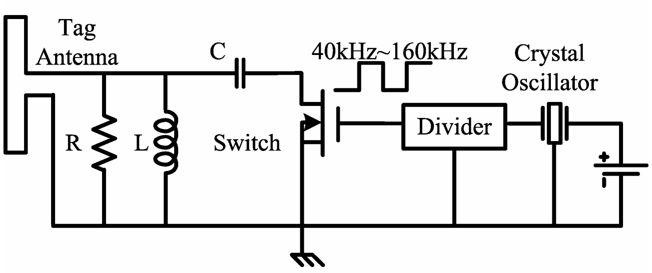

Fig. 5. Backscatter modulator

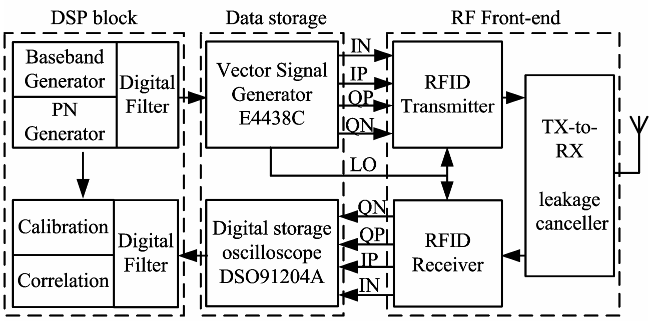

Fig. 6. Measurement setup scheme

A testing plan has been established and measurement setups have been carried out. The testing process can be divided into the following two steps. The first step is to check the function of the designed reader. The measurement setup scheme is illustrated in Fig.6. In this step, a continuous sine wave is generated and transmitted by the reader. Basic performances of a passive UHF RFID system are tested and analyzed, including the output power, isolation, reader sensitivity and etc.

The second step is to validate the proposed real time locating system. To simplify the communication process, we start from the forth step of the chart flow in Fig.3, assuming that the reader has interrogated a tag which needs to be located. PN sequences are loaded into a Vector Signal Generator (Agilent E4438C) and sent to the RFID transmitter through I/Q channels. The received signal is down-converted by a I/Q demodulator and stored in Digital Storage Oscilloscope (Agilent DSO91204A). The length of the PN sequence (Golden code) is 31, while the symbol rate is 2.48 MHz. However, the sampling frequency is 158.72 MHz, with an over-sampling ratio of 32. The demodulated data is then processed in Digital Signal Processing to calculate the TOA and to estimate the distance.

IV. RESULTS AND DISCUSSION

A. Basic performances

The fabricated reader and tag are shown in Fig.7 and basic performances of passive UHF RFID system are measured and provided by Table I. Measurement results without leakage canceller are also presented in the table to compare with the final values. The TX-to-RX isolation has been increased from 25 dB to 42.5 dB within UHF RFID frequency band of 920-925 MHz.

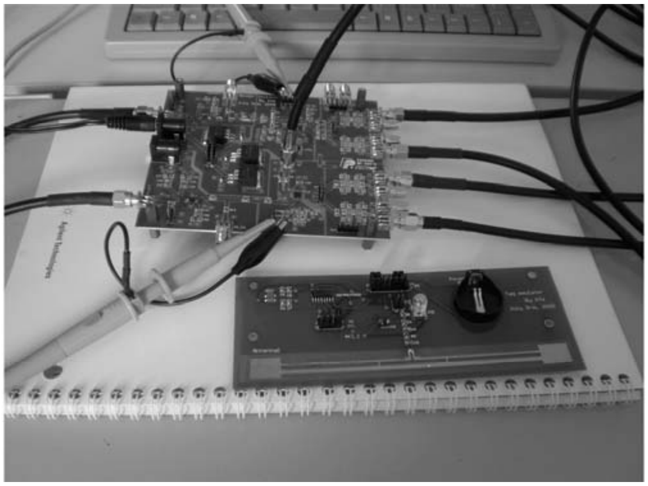

Fig. 7. Fabricated reader and tag

TABLE I
BASIC PERFORMANCES

Parameter	Without leakage canceller	With leakage canceller
AM modulation depth	18.2%	18.2%
Data rate	78.6 Kbps	78.6 Kbps
Isolation	25 dB	42.5 dB
Output power	29 dBm	26 dBm
Channel loss	40.6 dB	46.2 dB
Reader sensitivity	-52.2 dBm	-66.4 dBm

As a result, reader sensitivity has been improved from -52.2 dBm to -66.4 dBm. It should be noticed that reader sensitivity is not measured in the real communication channel because it will be degraded due to the effect of reflections and interferences. Thus, it is hard to precisely measure it in the real scenario. Instead, the reader and tag are directly connected by a variable attenuator. The measured output power of the reader with leakage canceller is 26 dBm. Considering a maximum BER of 1.0e-3, the maximum channel attenuation is 46.2 dB. Thus, reader sensitivity can be calculated by [10]:

$$P_{sensitivity} = P_{output} - 2P_{channel} + G_{reader} + r \qquad (1)$$

where G_{reader} represents the reader antenna gain and r represents the reflection coefficient of the target tag. The measurement sensitivity is worse than the theoretical value in that the AM modulation depth of the tag and the output power are less than the anticipated values.

B. System verification

The final measurements have been carried out in a real scenario to validate the proposed real time locating system. The environment where the measurements have taken place is a typical multi-path environment composed of tables, ceiling, floor and walls. Thus, multiple bad effects will take place during the measurements, which deteriorate the system performances and reduce the overall accuracy. Fortunately main of these effects have been considered and modeled in the system.

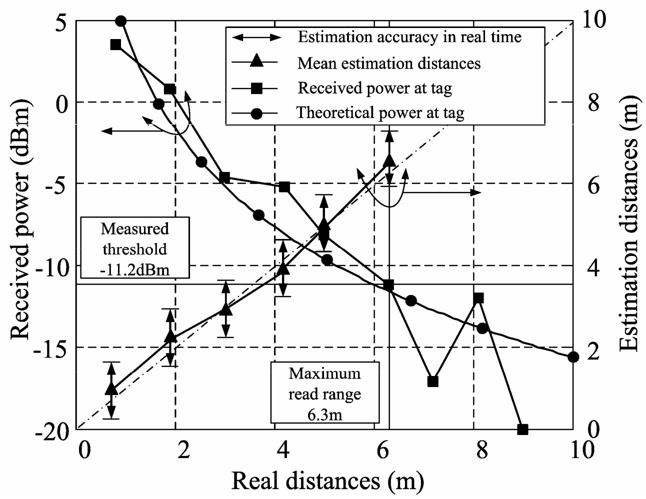

Fig. 8. Measurement results

To get a correct measurement, the reader needs to know about delays through the antenna, the cables and the amplifiers. Any change in cable length is going to cause an error which needs to be corrected. Thus a calibration is required to eliminate the system error and the above mentioned phase shift caused by the tag modulator. The calibration steps are as follows. First, put a tag at the calibration distance (5 meters, for example) and measure the TOA under this setting. Second, calculate the inherent time delay in the system and record it. Practically, the calibration settings are saved on the EPROM in the processor and they will be valid for all further measurements until there is a change in cabling or antennas.

Fig.8 illustrates received power at tag and estimation distances versus real distances. The theoretical values are also given to compare with these results. It is clear that the maximum read range is 6.3 meters, and that the corresponding power at tag is -11.2 dBm, which represents the system sensitivity since the reader sensitivity can't be tested in a real scenario. This result is larger than that of the scenario without antenna (-16 dBm) due to the mismatch at the tag antenna.

Fig.8 also indicates that the estimation accuracy in real time is about 1.6 meters and the mean estimation error of 1000 times' measurement is limited in 0.5 meter. The mean estimation error at 5 meters is nearly zero because it is the calibration distance. Since the total time of 1000 times' measurement is less than 1 second, mean values can be reported every 1 second, and the overall accuracy will be kept in 0.5 meter. The standard deviation of the estimation error is given by [11]:

$$\sigma_{\Delta} = cT_{\mathrm{C}}\sqrt{\frac{1}{4mT\cdot C/N_0}} \tag{2}$$

where c is the light speed $3\times10^8 m/s$, T_C is the symbol rate of PN sequence, T is the average time, m is the over-sampling rate, and C/N_0 is received Signal-to-Noise ratio.

V. CONCLUSIONS

A TOA-based real time locating system using passive UHF RFID has been presented in the paper. A reader architecture based on a direct conversion transceiver and a tag modulator based on backscattering have been developed and implemented to make up of a complete passive UHF RFID-based real time locating system. PN sequences have been used to measure the TOA and estimate the distance between reader and tag. A TX-to-RX leakage canceller has been applied in the reader RF front-end to increase the isolation and enhance the sensitivity.

Measurement setups have been built in a typical multi-path environment. Measurement results indicate that the maximum read range of the system is 6.3 meters, and that the estimation accuracy in real time is about 1.6 meters. However, the mean estimation error of 1000 times' measurement in 1 second is less than 0.5 meter. Thus, the distance of the tag can be derived with high accuracy in time that is close to real time.

As a result, the proposed passive UHF RFID-based RTLS has proved to range all the tags in its effective operation area in nearly real time, and it will locate and track the tags if Direction of Arrival (DOA) should be precisely detected. The latter will be future research work.

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